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Research on Energy Efficiency Design Index for Sea-going LNG Carriers

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Abstract: This paper describes the characteristics of liquefied natural gas (LNG) carriers briefly. The LNG carrier includes power plant selection, vapor treatment, liquid cargo tank type, *etc*. Two parameters—fuel substitution rate and recovery of boil of gas (BOG) volume to energy efficiency design index (EEDI) formula are added, and EEDI formula of LNG carriers is established based on ship EEDI formula. Then, based on steam turbine propulsion device of LNG carriers, mathematical models of LNG carriers' reference line value are established in this paper. By verification, the EEDI formula of LNG carriers described in this paper can provide a reference for LNG carrier EEDI calculation and green shipbuilding.
Keywords: liquefied natural gas (LNG) carriers; regression analysis; energy efficiency design index (EEDI); reference line; LNG fuel vessels; regression platform

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1 Introduction

In 2008, Ship EEDI was first proposed instead of carbon dioxide (CO_2) design index by Marine Environment Protection Committee (MEPC) 58th meeting. EEDI was developed by the new shipbuilding CO_2 index, and formally adopted in MEPC 62nd meeting. At ship design stage, EEDI estimates CO_2 emissions generated per unit of ship traffic. Researches (Yang, 2013; Wang *et al*., 2013; Ozakiet *et al*., 2011; Cheng and Li, 2012) on EEDI have gradually increased in recent years.

Using LNG as ship fuel is a viable option by comparing Iceland's fishing fleet ship emissions of pollutants marine oil (MGO) and LNG. Some researchers considered environment, safety, fuel costs and other issues from the aspects of basic technology and experience of LNG fuel system, as one of the most promising alternative fuels is LNG in energy saving and high efficiency. Devanney (2011) pointed out that the transformation of the existing ship power system would produce better energy efficiency by researching Panamax container ship fueled by LNG transmission and powered plant. Liu *et al*. (2012a, 2012b, 2013) advised establishing the reference line according to the characteristics of the ship to provide reference for ship design.

With the increasing demand of international community for energy conservation (Huang *et al*., 2010; Qiu and Li, 2003; Zhou *et al*., 2011), LNG will be widely used as the main force of the new energy in the future. International Maritime Organization (IMO) (Wang and Wen, 2012; Livanos *et al*., 2014) actively researches and develops every new ship of energy efficiency design, which not only helps to build LNG green standards and norms and promote low-carbon energy-saving technology in LNG carriers, but also promotes healthy development of LNG fuel market.

With increasing energy consumption and greenhouse gas emission, the trend of global warming is getting worse. Adopting energy saving measures, formulating relevant standards and stepping into the low-carbon economy era have become the governmental focuses of the research. The shipbuilding industry consumes a lot of fuels and produces large amounts of CO_2 each year. Replacing the fuel by clean, efficient and environmental friendly fuel can effectively reduce the ships consumption. Liquefied natural gas (Liu, 2004), which has the advantage of low price and high efficiency, is used as an alternative fuel of the ship, which can save energy and reduce CO_2 emissions as well. The number of LNG carriers and LNG fuel vessels will increase quickly in the next few years (Lu, 2012).

EEDI has already been implemented as a mandatory standard. However, because of the particularity of LNG carriers, EEDI standard is not suitable for LNG carriers. Researching and formulating EEDI standard and reference line formula, which are suitable for LNG carriers, can effectively promote the development of LNG fuel in the shipbuilding industry.

This paper has analyzed the characteristics of LNG carriers and established EEDI formula and its reference line model, based on the definition of ship EEDI formula and reference line, providing a reference for the design and construction of LNG carriers.

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2 EEDI formula of LNG carriers

2.1 Characteristics of LNG carriers

Currently, EEDI formula does not apply to LNG carriers, because LNG carriers are different from other conventional ships. The concrete research aspects are as follows.

2.1.1 Special primary propulsion system

Steam power is the most common propulsion system of early LNG carriers, and it will play a dominant role for a very long time. The disadvantages of steam power, such as high fuel consumption, low thermal efficiency, lead to that it is replaced by other propulsion systems.

Table 1 lists the advantages and disadvantages of several alternative propulsion systems, and some of the devices have already been used in the real ship, which has achieved good results.

Table 1 List of the advantages and disadvantages of alternative propulsion system

Main propulsion	Advantage	Disadvantage	Efficiency /%
Steam turbine	High power, high reliability, long service life, low initial investment cost and maintenance cost	Limitations with external combustion, low thermal efficiency, poor mobility	30
Gas turbine	High efficiency, small weight and size, good mobility, high degree of automation	Low service life, high costs of operation and maintenance	40
Diesel engine with reliquefaction equipment	High thermal efficiency, high fuel efficiency, high reliability, long maintenance period	High initial investment costs, high operation and maintenance costs, low life expectancy	43–48
Dual fuel engine	High thermal efficiency, low fuel consumption, environmentally friendly, reliable	less optional space	>40
Electric propulsion	High thermal efficiency, low fuel consumption, mobility, environmentally friendly	Equipment increases, improve ship cost	>40

2.1.2 Handling system of boil of gas (BOG)

The biggest difference between LNG carriers and general civilian ships is that LNG carriers produce vapor-BOG.

1) Reasons for producing BOG.

Unloading LNG causes change to tank volume. The operating device transfers external environment heat to the tank, which causes temperature change. The tank pressure change leads to change in the gas-liquid equilibrium *etc*., which can produce a lot of vapor.

2) Harm of BOG.

BOG increases pressure of storage tank, which exacerbates evaporation rate of liquid cargo, destroys balance of the tank, and even forces the safety valve to open. The BOG emitting into the atmosphere will cause direct economic losses. If the valve fails, high pressure will harm cargo tank maintenance system, which even leads to more serious consequences.

3) Treatment processes of BOG.

The treatment processes of BOG are as follows:

a. Send the vapor in the LNG storage tank directly back to the cabin;

b. Send BOG flaring or into the atmosphere;

c. Condense BOG and then output it;

d. Directly compress BOG and then output it;

e. Liquefy BOG again, which needs to configure re-liquefaction equipment.

Evaporation gas is composed of both cargo and fuel. How to deal with vapor not only depends on owner's value judgment of BOG, but also relates to selection of the power plant. Given LNG carriers will inevitably produce BOG process in sail, giving priority to use BOG as the main fuel is the trend of power plant development. Currently there are several forms of power units: conventional low-speed diesel engine plus re-liquefier, natural gas/diesel double-fuel power plant, such as dual-fuel diesel/gas turbine plus electric propulsion.

2.1.3 Special cargo maintenance system

Since LNG is transported at −163 °C and volatile, improper transport and storage will bring leak, explosion, fire, frostbite and other hazards. The characteristics of high-risk cargo determine LNG ship differs from other conventional cargo ships in special cargo system, especially in cargo hold maintenance system. It is one of the main structural features of LNG ship. The type of cargo hold maintenance system is closely related with LNG evaporation rates, so LNG ships have more stringent requirements on hull structure and materials.

In addition, LNG carriers usually have a liquid or gas firmament, which is used for LNG cargo handling and recycling of volatile gas on the deck of the boat. Vapor in tank is cached to the gas firmament, in order to prepare for host fuel use. The tank size depends on the size of liquid tank volume and evaporation rate.

2.2 Establishment of EEDI formula

2.2.1 Create an EEDI formula

The MEPC.65 meeting discussed about the EEDI calculation formula of LNG carriers, agreed to make baseline formula according to diesel propulsion, diesel electric propulsion and steam turbine propulsion.

The most obvious difference of these three kinds of propulsion modes is that host fuel form is single fuel, single natural gas or a mixture of both. By analyzing and referring to a new ship building EEDI formula, it set the stage for an EEDI formula for LNG carriers to be established. The formula considers the following aspects:

1) Power system contains main propulsion and auxiliary system (diesel generators);

2) Total volume of LNG carriers' liquid cargo represents the ship's cargo capacity, taking into account the LNG transport ship liquid cargo tank and the volume equipped for LNG cargo handling;

3) Considering the power device is diversified and the evaporation gas in storage tank as a host fuel is a major trend of development in the future, the replacement rate of natural gas to fuel is introduced into formula.

Establish EEDI calculation formula of LNG carriers. Generally, one of the largest energy consumption conditions is considered:

$$\mathrm{EEDI}=\frac{\left(\prod_{j=1}^{n} f_j\right)\left(\begin{array}{l}\sum_{i=1}^{n\mathrm{ME}} P_{\mathrm{ME}(iO)}\cdot C_{\mathrm{FME}(iO)}\cdot \mathrm{SFC}_{\mathrm{ME}(iO)}\cdot(1-i)+\\ P_{\mathrm{ME}(iG)}\cdot C_{\mathrm{FME}(iG)}\cdot a\end{array}\right) (P_{\mathrm{AE}}\cdot C_{\mathrm{FAE}}\cdot \mathrm{SFC}_{\mathrm{AE}})+\left\{\left(\prod_{j=1}^{n} f_j\right)\cdot\sum_{i=1}^{n\mathrm{PTI}}P_{\mathrm{PTI}(i)}-\sum_{i=1}^{n\mathrm{eff}} f_{\mathrm{eff}(i)}\cdot P_{A\mathrm{Eeff}(i)}\right\}\cdot C_{\mathrm{FAE}}\cdot \mathrm{SFC}_{\mathrm{AE}}-\sum_{i=1}^{n\mathrm{eff7}} f_{\mathrm{eff}(i)}\cdot P_{\mathrm{eff}(i)}\cdot C_{\mathrm{FME}}\cdot \mathrm{SFC}_{\mathrm{ME}}}{f_i\cdot\rho\cdot(\mathrm{Capacity}+b)\cdot V_{\mathrm{ref}\,c}\cdot f_w} \quad (1)$$

In the formula, the subscript ME stands for host parts, AE auxiliary parts, O emissions of carbon dioxide which is the host combustion fuel, the subscript G stands for emissions of carbon dioxide which is the host combustion BOG.

i: Fuel substitution rate, the reduced percentage when natural gas is used instead of fuel, if host is low speed diesel propulsion, then i=0, if host is natural gas propulsion, then i=1.

a: For dual fuel host combustion, how much BOG is used per unit time unit power. If caloric value of diesel engine is completely replaced by natural gas, the standard low calorific value of fuel is 42 700 kJ/kg, standard low calorific value of natural gas is 48 000 kJ/kg, then:

$$P_{\mathrm{ME}}\cdot \mathrm{SFC}_{\mathrm{ME}}\cdot 42700\cdot i=P_{\mathrm{ME(LNG)}}\cdot a\cdot 48000$$

$$a=0.89\cdot \mathrm{SFC}_{\mathrm{ME(FO)}}\cdot i$$

Capacity is the volume of LNG liquid tank, m^3; b the volume of the liquid or gas firmament, for cargo loading and BOG recycling, m^3; ρ the density of liquid methane, g/cm^3; V_{ref} the speed of ship, kn;

This paper takes a vapor turbine propelled LNG carrier as an example. It is usually equipped with two sets of boilers and a steam turbine. Boilers use BOG as fuel, and steam turbine transforms heat energy into mechanical energy, then drives generator to work. So the host uses natural gas, then in Eq. (1), i=1. If not considering reduction of carbon emissions of boilers and using innovative energy technology, then the maximal energy consumption condition in LNG carrier will be:

$$\mathrm{EEDI}=\frac{\left(\prod_{j=1}^{n} f_j\right)\left(\sum_{i=1}^{n\mathrm{ME}} P_{\mathrm{ME}(iG)}\cdot C_{\mathrm{FME}(iG)}\cdot \mathrm{SFC}_{\mathrm{ME}(iG)}\right)+(P_{\mathrm{AE}}\cdot C_{\mathrm{FAE}}\cdot \mathrm{SFC}_{\mathrm{AE}})}{f_i\cdot\rho\cdot(\mathrm{Capacity}+b)\cdot V_{\mathrm{ref}\,c}\cdot f_w} \quad (2)$$

where SFC is gas consumption rate, related to host selection, g/kWh; Capacity the volume of LNG liquid tank, m^3; ρ the density of liquid methane, g/cm^3.

2.2.2 Calculation example

Select 'AL BIDDA LNG Carrier' equipped with a steam turbine power plant as an example, the main scale and performance parameters are shown in Table 2.

According to the above information, calculate the EEDI, the parameter values are shown in Table 3.

Table 2 Main dimensions and performance of AL BIDDA LNG Carrier

Items	Values	Items	Values
L_{oa}/m	297.5	Capacity/m^3	137 339
L_{pp}/m	283	V/($m\cdot s^{-1}$)	21.3
B/m	45.75	GT/t	111 124
D/m	25.55	Number of host/set	1
d/m	11.25	MCR/kW	26 800
DW/t	72 462	Diesel generator/kVA	5×1 070

Table 3 EEDI calculation

Computational item	Results	Computational item	Results
V_{ref}/kn	21.3	C_{FME}	2.75
Capacity/m^3	137 339	C_{FAE}	3.207
MCR_{ME}/kW	26 800	SCF_{AE}/(g/kWh)	210
SCF_{ME}/(g/kWh)	169	f_i	1
P_{ME}, 75%MCR_{ME}/kW	20 100	f_j	1
P_{AE}/kW	920	f_w	1
b/m^3	13 740	EEDI/ (g-CO_2/tone nmile)	6.88

3 Reference line formula of new LNG carriers

EEDI is a tool to measure CO_2 emission level in ship design and construction process, and EEDI reference line value is a tool to determine whether ship CO_2 emissions meet the requirements or not. MEPC.203 (62) resolution provides that the EEDI value of the newly built ships must be less than or equal to reference line value. In this article, according to the effectively collected data, the regression analysis of the calculation results based on EEDI formula have already been established, trying to set up a reference line formula to determine whether LNG carrier CO_2 emissions meet the standard.

3.1 Establishment of the reference line regression model

72 LNG ships are collected in this paper, including 39 LNG carriers. The data is divided into two sections by construction time. Using cargo volume as the independent variable, this paper does some regression analysis of LNG carriers' EEDI values, and the results are shown below.

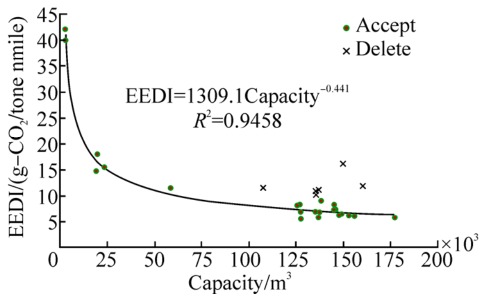

Fig. 1 Number of samples *N*=39, year 1969–2013

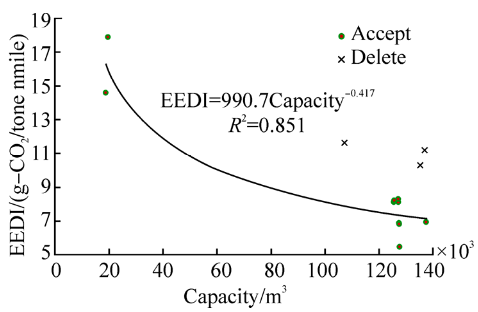

Fig. 2 Number of samples *N*=17, year 1969–1999

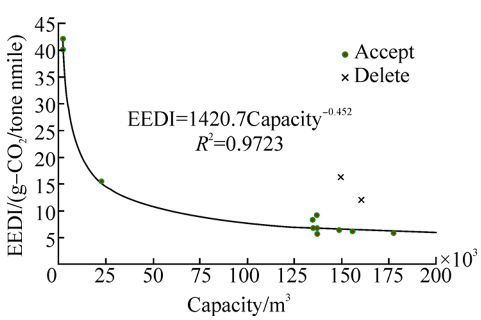

Fig. 3 Number of samples *N*=22, year 2000–2013

Mathematical model is summarized in Table 4 as shown below:

Table 4 Mathematical model

Construction time	Regression formula	Correlation coefficient
1969–2013	EEDI=1 309.1Capacity$^{-0.441}$	R^2=0.945 8
1969–1999	EEDI=990.7Capacity$^{-0.417}$	R^2=0.851
2000–2013	EEDI=1 420.7Capacity$^{-0.452}$	R^2=0.972 3

3.2 Verification of reference line formula

The validation of mathematical model with capacity as independent variable data is shown in Table 5.

Table 5 Validation of mathematical model with capacity as independent variable

Ship ID	Capacity/ m^3	EEDI	Reference line value	Error/ %
AL DEEBEL	145 000	7.349	6.931	−5.68
SERI	152 888	6.143	6.771	10.23
AL BIDDA	137 339	6.879	7.099	3.20
BINTULU	18 927	14.753	17.013	15.32
DWIPUTRA	127 386	6.884	7.339	6.61
ECHIGO	126 911	8.159	7.351	−9.91
NOTUS	137 006	5.725	7.107	24.14
SOHAR LNG	137 248	6.726	7.101	5.58
WILENERGY	126 885	8.357	7.351	−12.04
SURYA AKI	19 538	17.991	16.776	−6.75
SATSUMA	23 097	15.523	15.583	0.39

Seen from Table 5, error is within the permitted range between reference line value and actual EEDI value, so this reference line formula can provide a reference for EEDI calculation of LNG carrier's energy efficiency and green computing in shipbuilding.

4 Sensitivity analysis of EEDI formula

It can be seen from EEDI formula in addition to using the technology of innovation in energy efficiency that equipped with waste heat recovery unit, the main factors influencing EEDI value are P_{ME}, b, Capacity and V_{ref}.

In order to study the influence degree of various factors on EEDI formula, selecting "Abadi" LNG carrier as an example and analyzing the effect of each factor change on EEDI formula values of LNG carriers. The main parameters are shown in Table 6.

Table 6 Main parameters of "Abadi"

Items	Values	Items	Values
L_{oa}/m	290	Speed/kn	19.5
B/m	46.3	GT/t	117 461
D/m	27	Capacity/m^3	135 000
b/m^3	13 500	Power/kW	28 985
Dead weight/t	72 758		

4.1 The impact of P_{ME} on EEDI

To analyze the impact of the main propulsion devices' power on EEDI formula value, keep speed, cargo capacity, gas consumption and other factors remain unchanged, and change the magnitude of power to observe changes in EEDI value. Variation of the power change is selected as 10%, 8%, 8%, 4%, 2%, 0%, 2%, 4%, 6%, 8%, and 6%. The data is shown in Table 7. The data is plotted in the form as shown in Fig. 4.

Table 7 Computation of the impact of *P* on EEDI value

No.	*P*/kW	Power change/%	EEDI	EEDI change/%
1	26 086.5	−10	7.400	−9.86
2	26 666.2	−8	7.562	−7.89
3	27 245.9	−6	7.723	−5.92
4	27 825.6	−4	7.885	−3.94
5	28 405.3	−2	8.047	−1.97
6	28 985.0	0	8.209	0.00
7	29 564.7	2	8.371	1.97
8	30 144.4	4	8.533	3.94
9	30 724.1	6	8.694	5.91
10	31 303.8	8	8.856	7.89
11	31 883.5	10	9.018	9.86

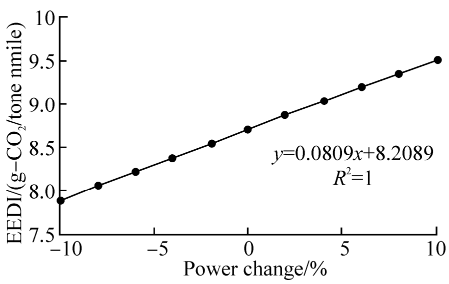

Fig. 4 Computation of the impact of *P* on EEDI value

4.2 The impact of Capacity on EEDI

The impact of capacity on EEDI data is shown in Table 8. The data is plotted in the form as shown in Fig. 5.

Table 8 Computation of the impact of Capacity on EEDI value

No.	Capacity/m^3	Capacity change/%	EEDI	EEDI change/%
1	121 500	−10	9.030	10.00
2	124 200	−8	8.853	7.84
3	126 900	−6	8.683	5.77
4	129 600	−4	8.519	3.77
5	132 300	−2	8.361	1.85
6	135 000	0	8.209	0.00
7	137 700	2	8.062	−1.79
8	140 400	4	7.921	−3.51
9	143 100	6	7.784	−5.17
10	145 800	8	7.652	−6.78
11	148 500	10	7.525	−8.33

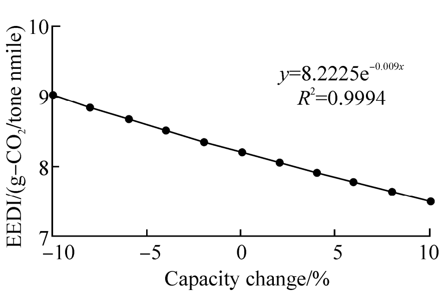

Fig. 5 Computation of the impact of Capacity on EEDI value

4.3 The impact of V_{ref} on EEDI

The impact of speed on EEDI data is shown in Table 9. The data is plotted in the form as shown in Fig. 6.

Table 9 Computation of the impact of speed on EEDI value

No.	V_{ref}/kn	V_{ref} change/%	EEDI	EEDI change/%
1	17.55	−10	9.121	11.11
2	17.94	−8	8.923	8.69
3	18.33	−6	8.733	6.38
4	18.72	−4	8.551	4.17
5	19.11	−2	8.376	2.04
6	19.50	0	8.209	0.00
7	19.89	2	8.048	−1.96
8	20.28	4	7.893	−3.85
9	20.67	6	7.744	−5.66
10	21.06	8	7.601	−7.41
11	21.45	10	7.463	−9.09

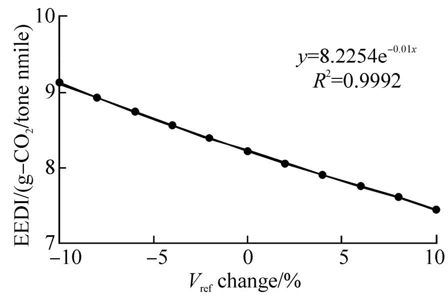

Fig . 6 Computation of the impact of speed on EEDI value

4.4 The impact of *b* on EEDI

The impact of *b* on EEDI data is shown in Table 10. The data are plotted in the form as shown in Fig. 7.

Table 10 Computation of the impact of b on EEDI value

No.	*b*/m^3	*b* change/%	EEDI	EEDI change/%
1	12 150	−10	8.284	0.92
2	12 420	−8	8.269	0.73
3	12 690	−6	8.254	0.55
4	12 960	−4	8.239	0.36
5	13 230	−2	8.224	0.18
6	13 500	0	8.209	0.00
7	13 770	2	8.194	−0.18
8	14 040	4	8.179	−0.36
9	14 310	6	8.164	−0.54
10	14 580	8	8.150	−0.72
11	14 850	10	8.135	−0.90

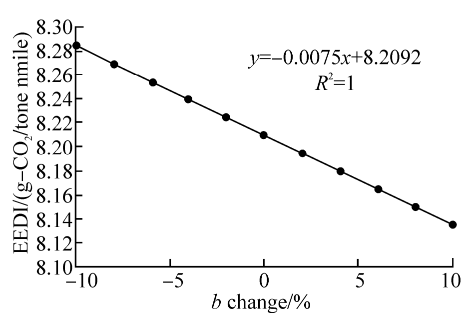

Fig. 7 Computation of the impact of *b* on EEDI value

The impact of above four sectors on EEDI formula is concluded in Table 11. Summary of various factors' impact on EEDI value is shown in Fig. 8.

Table 11 Summary of univariate sensitivity analysis

LNG carrier	Basic program	*P*/kW		Capacity/m^3		*V*/kn		*b*/m^3	
		10%	−10%	10%	−10%	10%	−10%	10%	−10%
EEDI value	8.209	9.018	7.4	7.525	9.03	7.163	9.121	8.135	8.284
Change/%		9.86	−9.86	−8.33	10	−9.09	11.11	−0.9	0.92

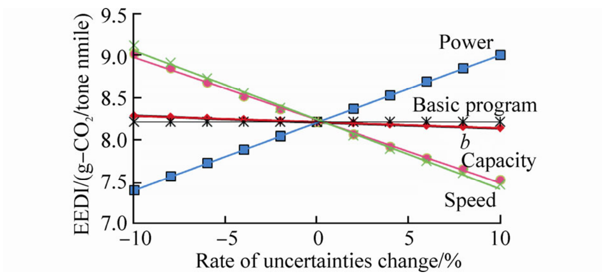

Fig. 8 Influence of different factors on the EEDI value

Analysis of the results can be concluded:

1) The greatest impact on EEDI is power, *P* reduces 10%, and EEDI reduces 9.86%

2) Second, *V* increases 10%, EEDI reduces 9.09%

3) Third, Capacity increases 10%, EEDI reduces 8.33%

4) The last, *b* increases 10%, EEDI reduces 0.9%

In this section the impact of a single variable on LNG carriers' EEDI value is simply studied. It has some limitations, and specific impact needs to be studied in depth.

5 Conclusions

In this paper, EEDI calculation model and reference line formulas for LNG carriers are established according to the unique features of LNG carriers, based on traditional EEDI formula. This LNG EEDI formula system is beneficial to low-carbon environmental protection, energy efficient LNG carriers design and development, reducing carbon emissions, as well as promoting the application of low-carbon technologies in LNG carriers. By verification, the new formula can provide a reference for EEDI calculation of LNG carrier's energy efficiency and green computing in shipbuilding. But there are not enough data, and doing a single variable sensitivity analysis has some limitations, more studies should be done to modify the formula in future.

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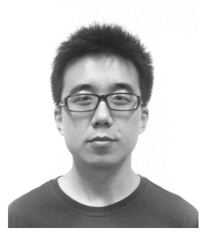

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